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Electric Propulsion Research and Development at JPL

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Electric propulsion enables many missions that satisfy the strategic goals of JPL and NASA to explore our Solar System, to detect "other earths" in neighboring planetary systems, and to search for life beyond the confines of Earth. Electric propulsion (EP) technology development at JPL is designed to support these types of JPL missions by introducing and infusing new technologies into JPL projects. In this paper, we will describe the EP technologies of interest and our role in developing and interjecting these technologies into JPL missions. Our technical approach is to understand the basic physics of the devices with sufficient fidelity to provide performance and life models critical to mission planning and assurance. In some cases, advanced capabilities and unique facilities enable us to lead in the development of the thruster technology. In addition, we actively investigate the EP plume interactions with spacecraft to ensure that the instruments and power components not compromised by the EP system and that the mission goals can be satisfied.

I. Introduction

ELECTRIC propulsion provides capabilities necessary to perform some of the more challenging missions of interest to NASA and JPL. These capabilities are applicable a large range of missions from micro-thrust for precision formation flying, to solar electric propulsion (SEP) for primary propulsion of near-Earth missions or satellite positioning, to high power nuclear electric propulsion (NEP) for deep space primary propulsion, and to mega-watt class thrusters for exploration missions.

Electric propulsion can provide the high delta-v required for very challenging NASA missions at specific impulses (Isp) of 1000 to 10,000 sec. Figure 1 shows the post launch delta-v required for some example past NASA missions and several proposed new missions. Chemical propulsion provided only a few km/sec Δv for missions such as Galileo and Cassini. Solar electric propulsion will provide 10 km/sec Δv for DAWN after its launch next year, and is proposed for other planetary missions where Δv's of up to 30 km/sec are required. Discovery and New Frontier missions are being proposed using SEP to provide the Δv required for complicated maneuvering and multi-body encounters. Deep space missions shown as examples in the figure to some of the outer planets require Δv's of 50 to 100 km/sec, which can be provided efficiently by NEP. A detailed description of the JPL EP missions and their thruster requirements are given in an accompanying paper[1].

There is considerable SEP experience in the aerospace industry for orbit insertion and station keeping of communications satellites. Boeing has a hundred Xenon Ion Propulsion system (XIPs)[2] ion thrusters in orbit on 25 communications satellites, and their second generation 25 cm ion thruster has performed flawlessly[3] over the past 5 years. Loral Space Systems has four Russian SPT Hall thrusters operating in space on one communications satellite, and recently completed a second SEP satellite that was successfully launched into orbit. There are also many other SEP communications satellite launches planned by industry in the next few years. These commercial thrusters operate in the 400-to-4500 W range at Isp's of 2000 to 3600 sec, and have typical required service life of 5000 to

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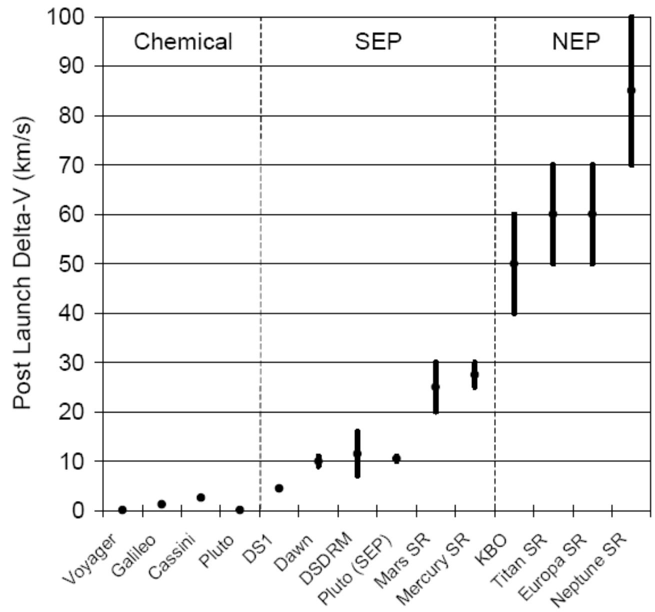

Figure 1. Post launch delta-v required for some past NASA missions and several proposed new missions.

15,000 hours. While the NASA Discovery-class SEP missions operate over the same power and Isp range, the requirements on life can approach ten times that of communications satellites. Other NASA proposed missions, like the NEP and Exploration missions, require 10 to 100 times the power of commercial systems. However, NASA precision formation flying and inspector spacecraft missions require micro-Newtons of thrust and precise controlled impulse. In addition, JPL missions often have sensitive scientific instruments on board that must be protected from thruster plumes and impurities. These advanced requirements over the industrial state-of-the-art are the subject of JPL's electric propulsion group research and technology development efforts.

This paper describes the JPL electric propulsion research and technology development programs for precision flying, SEP, NEP and Exploration applications.

II. Brief Mission Survey

Electric Propulsion technology development at JPL can be divided into four basic categories based on mission type or size. The four general mission types are shown in Table 1. Precision Formation Flying utilizes small colloid and miniature ion thrusters that provide precise thrust and impulse with less than about 50 W of operating power. Discovery and New Frontier Missions encompass the present Solar Electric Propulsion (SEP) missions and thruster technology presently being flown by NASA, such as DAWN, and by commercial industry for station keeping of communications satellites. These thrusters are roughly in the 0.5-to-5 kW class, although power levels are increasing as electric thrusters are used for both orbit insertion and station keeping. Prometheus and cargo class mission use high-power ion and Hall thrusters operating in the range of 10-to-50 kW for primary propulsion of large spacecraft for deep space missions. These missions are presently anticipated to utilize nuclear electric propulsion, although large solar arrays have been proposed to provide the power for cargo missions to the moon and Mars. Finally, Exploration Missions use very high power MPD and Hall thrusters for primary propulsion. While these are envisioned initially for cargo, the high thrust enables manned missions to be considered.

Table 1. Categorized thrusters by mission class with the power shown as order of magnitude.

		Thruster Type				
Mission Class	**Power (W)**	**Colloid**	**Ion**	**Hall**	**MPD**	**Plumes**
Formation Flying	**50**					
Discovery Class	**5000**					
Prometheus	**50000**					
Exploration	**500000**					

There is also a fifth category, spacecraft-plume interactions, which encompasses all JPL missions. With the energetic and often divergent plumes of varying species that come from electric propulsion thrusters, plume modeling and diagnostic technologies can help assess and mitigate potential issues with spacecraft interactions. The results of the modeling and plume measurements on the ground and in flight are incorporated into spacecraft engineering design tools and infused into JPL flight projects.

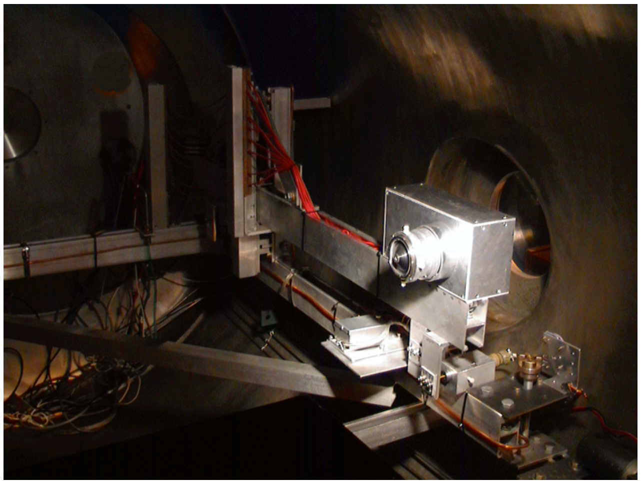

Figure 2. JPL Micro-thrust test stand.

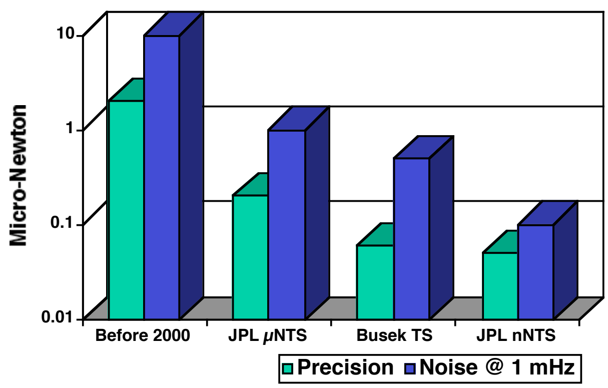

Figure 3. Graphic representation of micro-thrust stand development, where present missions require about 0.1 Newton resolution.

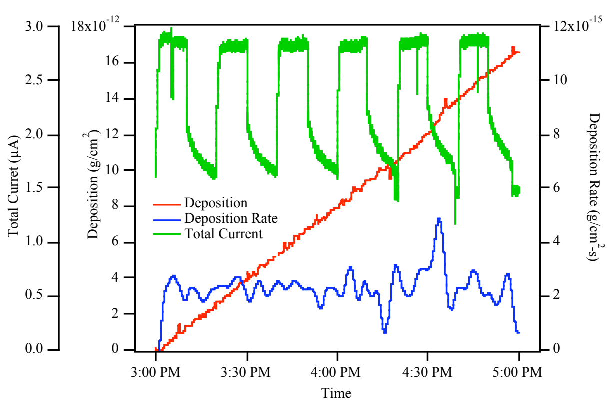

Figure 4. Total current and deposition rate for the ST7 colloid thrusters.

III. Precision Formation Flying

The overall goal of the micro-propulsion efforts at JPL are to provide missions Drag-Free and Precision Formation Flying Missions propulsion systems that meets or exceeds the exacting needs required to achieve their new science objectives. The present JPL missions that use our expertise are ST7-DRS, LISA and TPF, where the Advanced Propulsion Group provides requirements definition, propulsion system selection, technology development and testing of micro-thrust propulsion systems. JPL has world leading expertise in microthrust measurements that is applied to these projects. Figure 2 shows a photograph of the JPL Microthrust Test Stand, which is capable of measurements with micro-Neutron resolution. Figure 3 shows the progress on thrust stand development, where the need of some of the above missions is about 0.1 micro-Newton or lower. The JPL nano-Newton test stand, when completed, will provide 50 to 100 nano-Newton resolution.

JPL also has the only facility of its kind in the U.S. for the development and testing of microthrusters. The Microthrust Propulsion Laboratory (MPL) opened in FY04. It represents the world's largest UHV facility for testing microthrusters, and provides a Class-10 clean room environment with the necessary UHV vacuum systems to test FEEP and Colloid thrusters. The facility will also house the Nano-Newton Thrust Stand for performance measurements, exhaustive beam profiling and contamination diagnostics, and a load-lock system for rapid turn around and in-situ thruster inspection.

JPL is collaborating with Busek Co, Inc, in the development of a colloid thruster system[4] for disturbance reduction for the ST7-DRS Project. The thrust range requirement is 5 to 30 μN with a resolution of less than 0.1 μN and low thrust noise. The thrusters must have a life of 2750 hours and produce a contamination level of less than 0.1 $\mu g/cm^2$ at greater than 45° from the thrusters. Busek is presently fabricating the flight hardware for this mission, and JPL is providing laboratory and engineering model hardware tests, and feed system expertise.

The ST7-DRS project also required a demonstration of compliance with the ESA contamination specifications. Contamination and mass deposition measurements had never been made to the level of this specification before on colloid thrusters, so JPL developed a precision 2-D deposition monitoring system specifically for this device. Figure 4 shows measurements of the total current and deposition rate for the colloid thruster. The measured average rate of 10^{-15}

Figure 5. MiXI 3 cm thruster.

g/cm^2-s is calculated to produce less than 0.01 μg/cm^2 over three months of operation, which meets and exceeds the ST7 requirement by over a factor of 10. JPL will perform acceptance testing and integration support of the flight hardware for ST7 in FY06.

The LISA flight program[4] requires 20 times the thruster life of the ST7 project, or roughly 55,000 hours of micro-thruster operation. It is impossible to demonstrate this duration of performance and life by the end of the technology phase of LISA. The LISA Microthruster Technology Development program at JPL will demonstrate thruster life using physics-based models validated by laboratory experiments. This will include "short term" (>8000 hour) wear testing starting in FY06 through FY09.

The third flight program in this area at JPL is the Terrestrial Planet Finder (TPF), where micro-propulsion provides the capability of precision formation flying for detection of "Earth-like" planets orbiting nearby stars. This distributed array of spacecrafts requires a nominal thrust of 1-to-5 mN with a life of 10,000 hours from a low-mass thruster subsystem, with greater than 75% propellant utilization efficiency and a performance of over 0.05 mN/W. The Miniature Xenon Ion Thruster (MiXI)[5] technology developed at JPL uniquely satisfies the requirements for this mission and is close to demonstrating the required performance. The low noise operation of an ion thruster, compared to PPT for example, and the non-contaminating noble gas propellant provides a low interaction, low contamination thruster system. MiXI is a 3-cm diameter gridded ion thruster that has already demonstrated the propellant efficiency required of the mission, and is close to satisfying the thrust/power and grid life specifications. Figure 5 shows a photo of the MiXI thruster. The Microthruster group at JPL will continue to develop the MiXI thruster and flight cathode technology for this device, and work toward life validation.

IV. Solar Electric Propulsion

JPL flew the first deep space SEP technology mission, DS1, in 1996, with the expressed goal of demonstrating electric propulsion with the NSTAR thruster[6]. The JPL EP group led the EP mission assurance effort, which culminated in the 30,000 hr Extended Life Test (ELT)[7] of the NSTAR engine. The successful flight demonstration and laboratory life test enabled the Discovery Mission DAWN to be approved and scheduled to launch in 2006 with three NSTAR thrusters and two Power Processing Units (PPUs) to provide 400 kg throughput. The SOA NSTAR engine[6] uses molybdenum grids with a maximum rated propellant throughput of 155 kg per thruster, and a maximum thrust of 91 mN and specific impulse of 3100 sec. However, the NSTAR thruster performance limitations and the high EP system costs encountered by DAWN and have adversely impacted potential applications in cost-capped Discovery and New Frontier missions.

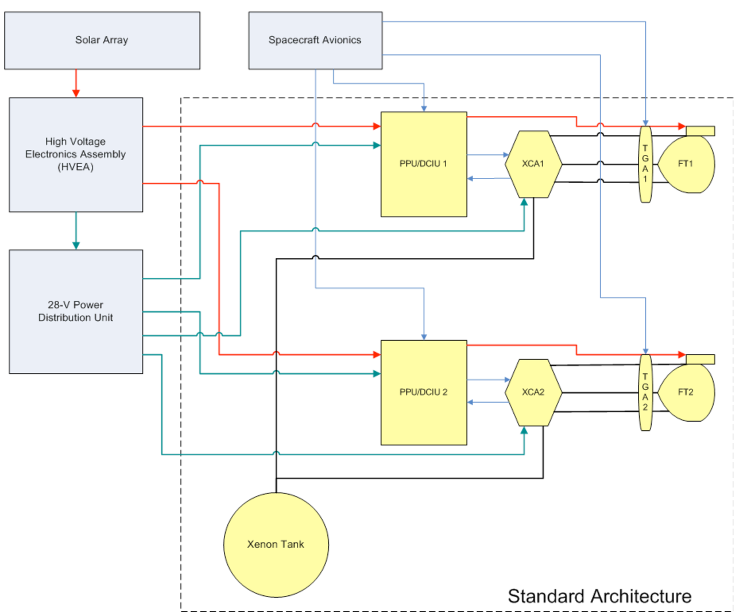

Figure 6. Standard Architecture layout showing single thruster/PPU/PMS strings.

The JPL Advanced Propulsion Group has a goal of increasing the probability that electric propulsion will be used in more missions within the constraints of cost-capped projects. This requires lowering the cost of ion propulsion systems and facilitating the introduction of advanced Ion Propulsion System (IPS) component technologies. This will be accomplished by extending thruster service life and performance to reduce IPS costs by eliminating redundant thrusters required to achieve mission throughput or thrust, developing an standardized IPS architecture that doesn't require component redesign for different missions, and providing a framework to introduce new component technologies that enhances capabilities and performance.

JPL is now driving the development of a Standard IPS Architecture, illustrated in Fig. 6, to reduce implementation costs for future users. A JPL-led team consisting of NASA centers (JPL, GRC and MSFC) and industrial participants down-selected from an enormous trade space to develop an EP Standard Architecture that defines the components used in EP subsystems. We have also defined cost and performance goals that include a 50% reduction in the IPS cost, a propellant throughput per thruster of 400 kg, a thrust of 119 mN, a maximum Isp of 4000 sec, a less expensive feed system and feed system cleaning process, and a more manufacturable, lower cost PPU. JPL has unique capabilities in ion thruster and feed-system design and testing, and extensive facilities for component and thruster testing, that will be applied to achieving these goals using NSTAR, improved NSTAR and NEXT ion thrusters. In addition, Hall thruster technology is being investigated for NASA SEP missions and incorporation in the Standard Architecture due to both their high thrust to power ratio and low implementation cost.

JPL is actively supporting the GRC-led NASA Evolutionary Xenon Thruster (NEXT)[8-10] development program. We have managed the development of the gimbal[11] for NEXT by an industrial contractor, and taken a leadership role in defining the grid-clearing requirements[12] for the NEXT ion engine and PPU. JPL has performed analysis of the ion trajectories and grid wear in support of the NEXT 2000 hr wear test[13] using the JPL-CEX ion optics programs, and carried out probabilistic failure analysis (PFA) to help determine the engine life and failure mechanisms. JPL has a leadership role in the System Integration Activities and Integration Test Measurements[14] for NEXT, and has performed extensive mission analysis in support of the applications studies. In addition, JPL leads the plume interactions investigations for NEXT in collaboration with SAIC and using their spacecraft-plume interaction code.

Finally, JPL is leading the efforts to upgrade the performance and life of the NSTAR engine for the Standard Architecture System applied to missions that don't require the higher power levels of the NEXT engine. The Carbon-Based Ion Optics (CBIO) program[15] has developed carbon-carbon composite grids for NSTAR that will increase the grid life by about a factor of five. Thruster performance and life modeling efforts at JPL, which use the extensive NSTAR data base from the ELT experiment to benchmark the codes, have predicted significant performance improvements can be obtained from relatively minor changes to the ion optics design and magnetic field. For example, a reduction in the diameter of the grid aperture array will remove under-utilized grid holes near the periphery, which eliminates local grid erosion from cross-over ions and increases the mass utilization efficiency by eliminating unnecessary gas leakage from these apertures. This is an obvious step from an examination of the grids at the conclusion of the ELT test. Figure 7 shows a photo of the engine after 30,253 hrs of operation, where backstreaming carbon from the beam dump has coated the grids. Only the center region of the grid is clean due to significant ion current density, and the outer several centimeters of the grid is blackened and coated due to the very low beam current density in this region. In addition, recent experiments have shown that relatively minor changes to the magnetic field design in NSTAR, consisting of strengthening some of the magnet rings and/or adding a fourth ring, can greatly improve the beam profile and reduce the discharge loss[16]. An improved profile decreases the peak current density on axis, which directly increases the grid life by reducing the aperture erosion rate. These and other reasonable changes in the engine will improve the thruster performance and life consistent with the goals of the Standard Architecture program.

Figure 7. Photograph of the NSTAR ion thruster at the conclusion of the ELT test.

V. Nuclear Electric Propulsion

Project Prometheus thruster performance and life requirements for deep space missions that use nuclear electric power far exceed the SOA in ion thrusters. Under a NASA NRA started in Jan. 2003, the JPL Advanced Propulsion Group designed and built the NEXIS thruster[17,18] aimed at meeting these goals. To date, the 57-cm diameter NEXIS thruster has demonstrated all these performance goals for a Project Prometheus 1 mission to the Jupiter Icy Moons

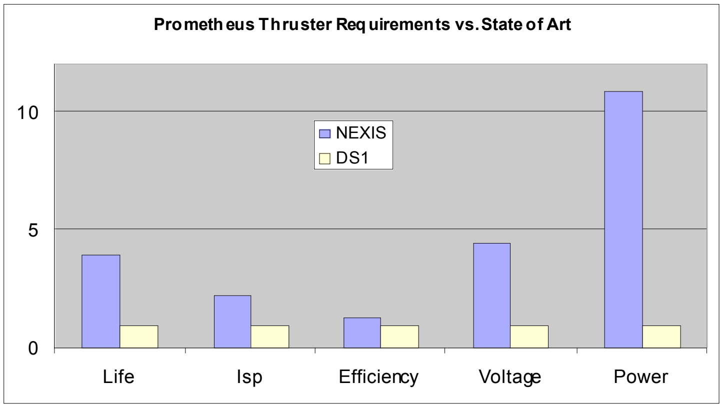

Figure 8. Prometheus thruster requirements compared to the demonstrated DS1 performance.

that uses eight thrusters operating simultaneously. Figure 8 shows the performance of the NEXIS engine compared to the DS1 SOA. Large improvement factors in life, power, voltage, and Isp are required. The NEXIS performance improvements over the SOA DS1 engine, described in Table 2, satisfy all the mission goals, with the exception of course of life where over 70,000 hours is required. A large effort is underway at JPL to understand and model the life and failure mechanisms of these thrusters.

The NEXIS thruster was the first ion thruster ever to be designed entirely using models based on plasma-discharge physics[19] and ion optics codes[20]. Figure 9 shows a photograph of the 57-cm-dia. NEXIS engine after assembly in the clean room. The thruster design features carbon-carbon composite grids, a conical-to-cylindrical anode geometry with six magnet rings, and a DC discharge hollow cathode to produce the plasma. The NEXIS thruster is designed for 15-year life utilizing the low-erosion rate CC grids, a graphite keeper assembly and a large-diameter, long-life dispenser hollow cathode[21]. NEXIS has been operated at up to 27 kW at 8700 s Isp, and demonstrated an overall efficiency of over 81% with an 82% beam flatness profile.

Table 2. NEXIS demonstrated performance for the proposed Prometheus mission compared to DS1.

	Life (hrs)	Isp (sec)	Efficiency	Voltage (V)	Power kW)
NEXIS	120,000	7,000	0.76	4,800	20.5
DS1	30,000	3,100	0.60	1,100	2.5

After these initial tests by a laboratory model (LM) thruster with both flat and domed CC-grids, JPL designed and fabricated two Development Model (DM) NEXIS thrusters intended to be flight-like and tested for performance and environmental integrity. The NEXIS DM structural design was performed by industry (Aerojet & L-3), and the thruster successfully passed Prometheus 1 EPS 3-Axis Proto-flight vibration at 10 Grms. These vibration tests verified the carbon-carbon ion optics structural design and validated the entire thruster structural design for flight[22]. The second DM thruster reproduced the performance of the LM thruster and demonstrated nominal performance at power levels up to 23 kW. After passing its performance tests, this thruster was put into a 2000 hr wear test in a thruster life-test facility at JPL. The thruster has successfully completed 1400 hrs to date without any significant change in the performance.

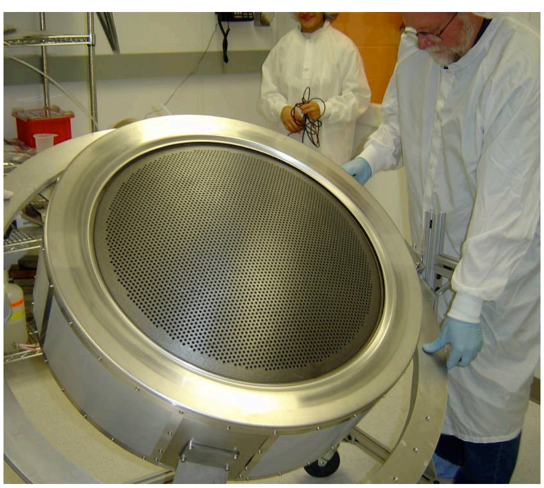

Figure 9. NEXIS 57 cm diameter ion thruster.

JPL is developing detailed computer models of ion thruster performance and life. The NEXIS discharge chamber design was performed using a JPL particle and energy balance model[19] modified from the original work of Brophy[23] to include anode sheath[24] and hollow cathode effects, and the commercial code Maxwell 3-D[25] to model the magnetic boundary. The model very accurately predicts the discharge chamber performance, as is seen in Figure 10, for three different discharge voltages tested. This 0-D model has recently been upgraded to a full 2-D neutral gas and plasma model of the discharge chamber[26]. Figure 11 shows an example of the 2-D plasma density predictions for the NSTAR engine. This code provides the first capability to model and predict plasma profiles and double ion spatial distributions, which are very important to the design of long life thrusters.

The ion optics in NEXIS are designed using the JPL-developed CEX-2D and CEX-3D codes[20], which model both the ion trajectories in the grids, the grid transparency and electron back-streaming limit, and the erosion of the grids due to ion bombardment. Figure 12 shows example ion trajectories from the CEX-2D code and pits and groves downstream erosion from the CEX-3D codes. The codes addresses both barrel wall erosion and the "pits and groves" surface erosion on the downstream face to provide complete predictions of grid life. These codes have been well benchmarked with the NSTAR LDT data and the NEXT 2000 hr wear test data, and provide life predictions with good accuracy. Analysis of the NEXIS grid indicates a 140,000 life, which is a factor of two over the requirement in order to account for any uncertainties in the models.

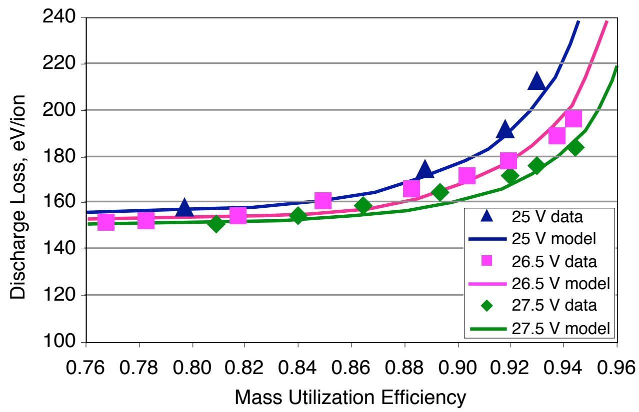

Figure 10. Performance curves for the NEXIS DM engine showing agreement between the design model and thruster performance.

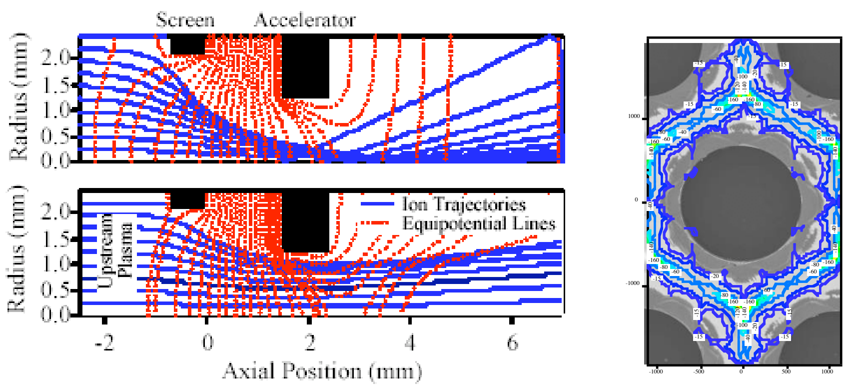

Figure 12. Example ion trajectories from the CEX-2D code (left) and "pits and groves" erosion pattern (right) from the CEX-3D code.

The cathode in NEXIS was designed using a 1-D cathode insert[27] and orifice model, which has recently been upgraded to a more accurate 2-D model[28]. Figure 13 shows a schematic of the model domain with the particle flows, and an example of plasma density predictions for the NEXIS cathode. A cathode life model was also developed[20] to predict the life of dispenser cathodes based on barium depletion of the insert. These models are benchmarked with laboratory experiments measuring the plasma parameters[29,30] and insert temperature[31] in-situ, and represent the first

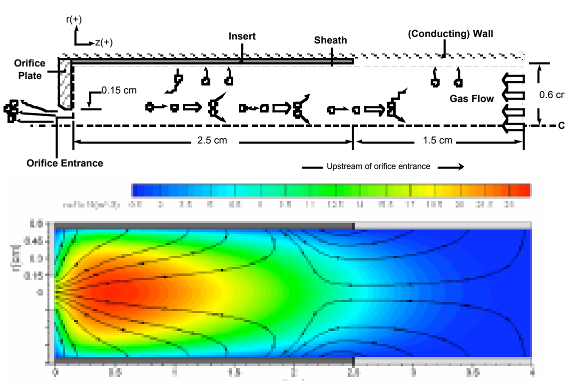

Figure 13. Cathode insert model left and an example of plasma density predictions inside the cathode (right).

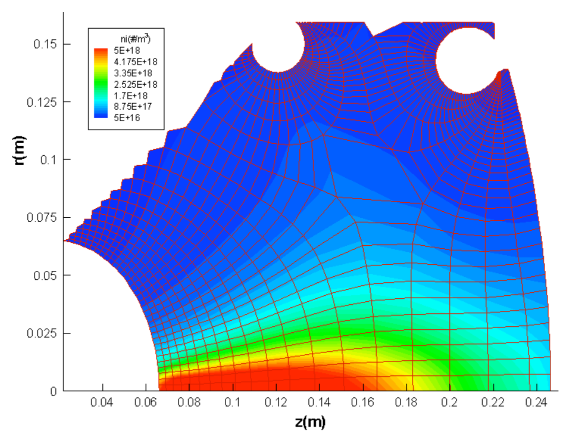

Figure 11. Plasma density prediction from the 2-D discharge chamber code for the NSTAR ion thruster.

models that can be used for hollow cathode design by providing accurate cathode performance and life predictions. Analysis of the NEXIS cathode at the nominal 28 A discharge current with the life model indicates that the cathode will provide the 70,000-hr Prometheus life with 50% margin.

The proposed Prometheus 1 mission will build on the success of JPL's modeling efforts and the NEXIS thruster in order to achieve the required life and performance. The 68-cm Herakles thruster[32] design, intended to satisfy Prometheus 1 mission goals using only six operating thrusters, is essentially a 20% scale-up of the NEXIS thruster, and was designed under JPL's leadership in collaboration with GRC using the codes described here. JPL's combination of modeling and experimental validation produces innovations in ion optics design, grid and keeper materials, discharge chamber design and cathode life modeling, that are essential to providing highly efficient thrusters that can meet the performance and life goals of NEP robotic missions.

VI. High Power Thrusters Exploration Missions

JPL is also developing very high power electric propulsion for Exploration Missions. The high-power EP research and development efforts at JPL are entirely mission-driven and aimed as post-Prometheus 1 robotic missions and lunar and Mars cargo missions in support of human exploration. JPL has unique expertise in electromagnetic propulsion and unrivalled facilities for developing high power, metal-vapor Hall and MPD thrusters. With the only large-scale facility in the country with over 2 MWe of power handing capability, JPL is focused on high power, condensable metal propellant thrusters. Figure 14 shows a photograph of the 3m dia. x 8 m long vacuum chamber in the metal-vapor thruster test facility. The facility is safety approved for handling reactive lithium propellants and also set up for operation with bismuth propellants.

Figure 14. Two MWe, metal-vapor thruster test chamber.

The current activities resulted from three NRA contracts:

- VHITAL: Very High Isp Thruster with Anode Layer; 25-36 kWe bismuth-fed Hall thruster.
- ALFA[2]: Advanced Lithium-Fed, Applied-field Lorentz Force Accelerator; 250 kWe electromagnetic accelerator with an applied magnetic field.
- CALIPPSO: Cargo vehicle Lithium Plasma Propulsion System, 500 kWe electromagnetic thruster with self-magnetic fields.

A. VHITAL

The VHITAL program[33], led by Stanford University and JPL, features a collaboration with the original Russian inventors of the two-stage bismuth Hall thruster 25 years ago to transfer the technology and produce significant improvements in Isp and power range in a new device over state of the art Hall thrusters. Figure 15 shows power, Isp and efficiency metrics for this class of thruster, illustrating the advances over the SOA obtainable from this two-stage Hall thruster technology. Figure 16 shows a photograph of the refurbished Russian TAL 160 thruster and a sketch of the VHITAL 160 thruster that will result from this program.

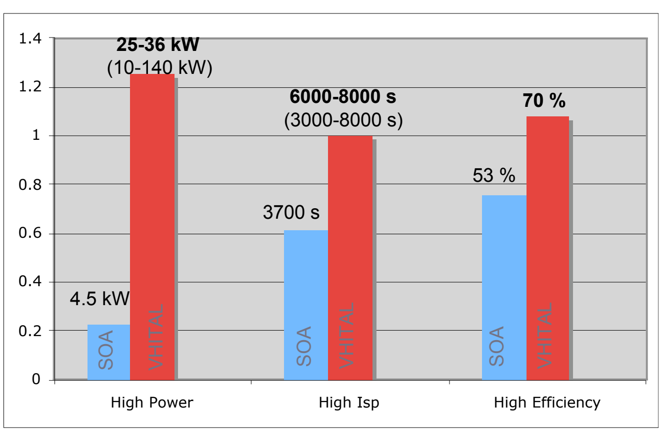

Figure 15. Power, Isp and efficiency comparisons for SOA Hall thruster and VHITAL.

The TAL-160 thruster and feed system have been refurbished at TsNIIMASH and the first stage successfully tested. The bismuth vaporizer and propellant isolator designs are complete and under construction at JPL. The bismuth vaporizer concept

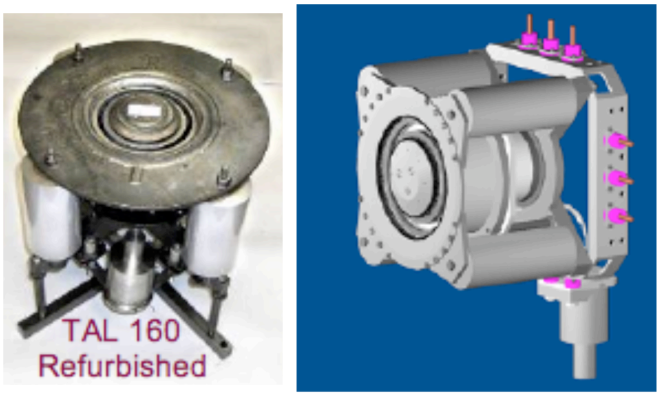

Figure 16. Russian TAL 160 thruster and VHITAL 160 schematic drawing.

and materials have also been successfully demonstrated and a new prototype bismuth heat pulse flow rate sensor has been built and undergoing testing at NASA MSFC. JPL is also developing a model of thruster second stage quasi-neutral plasma and investigating the life limitations of the device.

B. Lithium Lorentz Force Accelerators

Very high power propulsion systems enable many medium and far-term missions:

- Fast robotic outer planet missions
- Lunar and Mars cargo missions
- Piloted Mars missions
- Piloted outer planet missions

Two Lithium-fed Lorentz Force Accelerators (LFA's) are under investigation in collaboration with researchers from JPL for these missions because the basic physics of operation yields high power processing capability, and the properties of lithium provide very high efficiency and high Isp. In addition, electromagnetic acceleration allows over 200 times the power of the NSTAR ion engine to be processed in the same volume, resulting in relatively compact propulsion systems with a high specific mass and volume. Table 3 shows a comparison of metrics such as power, efficiency, Isp and life for the SOA MAI-MPD thruster and the two LFAs under development at JPL.

Table 3. Comparison of power, efficiency, Isp and life for SOA MPD thruster and the LFAs under development at JPL.

Metric	SOA MAI MPD-200	ALFA2	CaLiPPSo
Power/Thruster (kWe)	190	250	500
Efficiency (%)	48	60-63	>60
Specific Impulse (s)	4250	6200	4500
Lifetime (years)	---*	>3	>1

*Previous programs focused on engine performance

The efforts at JPL in this area address key challenges in electromagnetic thruster development. Comprehensive thermal design and modeling will permit the steady-state power levels to increase by a factor of 2 to 3. The efficiency will be increased by using lithium propellant, controlling Onset and optimizing the applied magnetic field. Multi-channel hollow cathodes will be investigated and developed to increase the life significantly. Finally, cooperation with mission analysts spacecraft designers at JPL will be used to understand the plume contamination issues, and mitigation techniques such as plume shields and booms will be investigated to minimize plume interactions.

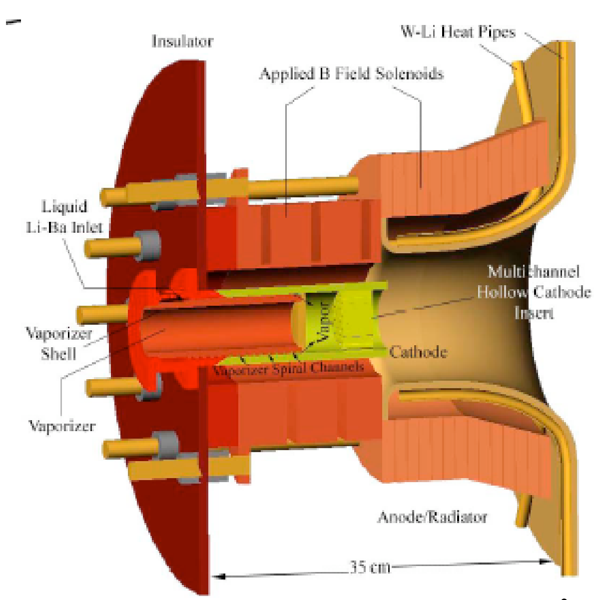

Figure 17. Conceptual design of the ALPHA^2 LFA thruster.

The conceptual design of the ALPHA^2 LFA thruster developed in the Phase I study program led by Princeton University in collaboration with JPL is illustrated in Fig. 17. The thruster utilizes an applied magnetic field and a multi-channel hollow cathode. The thruster performance analysis and conceptual design have been completed, and the cathode design is nearing completion. It is anticipated that construction will start early in Phase II in FY06.

CaLiPPSo is a 500-kWe LFA thruster development NRA program led by Boeing in collaboration with JPL. Such high-power, self-field lithium LFA thrusters have been found to provide the optimum Isp for Lunar and Mars cargo missions.

The CaLiPPSo thruster will utilize all-refractory metal construction that is radiation cooled, and incorporate advanced cathode technologies and to provide the required life. The program plan is to build a test a thruster to full power, and utilize analysis and short-term testing to assess life. The CaLiPPSo program was recently put on hold, but this technology will be revisited when interest in extending LFA technology to the 0.5 to 1 MW level re-emerges.

VII. Spacecraft and Plume Interactions

Interactions between electric propulsion plumes and the spacecraft have been of concern since this technology was first proposed forty years ago. Plume interaction issues are a potential problem for all of the different types of thrusters described in this paper that are under development for NASA spacecraft. In some thrusters, the ion beam plume is sufficiently wide to directly impact protruding spacecraft components such as solar arrays, antenna, instrument booms, etc. The fast ions in the ion beam can also collide with slow neutral atoms leaving thruster or neutralizer, and the collision products can have trajectories that intersect the spacecraft. This can cause deposition of undesirable materials from the thruster erosion such as molybdenum or carbon on the spacecraft components or instruments, or erosion of these same spacecraft components. Spacecraft erosion products can further contaminate the spacecraft.

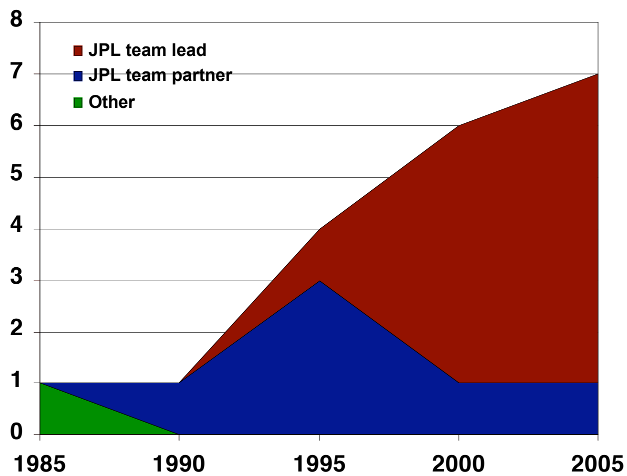

Figure 18. Number of plume investigations by year at JPL.

To eliminate or at least mitigate these effects, the JPL Advanced Propulsion Group has a program to model the plume and spacecraft processes, measure the plume parameters in ground tests and in flight to validate the models, and infuse the results into project planning and engineering design tools. This involves a cyclic process of making the instruments for diagnosing the plume characteristics, performing modeling of the plume and spacecraft interactions, making the measurements of the plume and benchmarking the models, and providing a valid plume model as an engineering tool to the spacecraft designers.

JPL has taken a leadership role in plume diagnoses and spacecraft-effects investigations over the past several years. Figure 18 is a graphic representation of the number of plume-related projects that JPL has been involved per year over the past 10 years. The infusion of additional expertise in plume diagnostics and spacecraft interactions, along with spacecraft effects modelers, has resulted in a large increase in the JPL workload in this area. The continuing interest in this area and the increasing number of on-going collaborations with universities, industry and government laboratories working in this field is indicative of NASA interest in implementing electric propulsion with minimal impact to the missions.

VIII. Conclusion

JPL has a significant effort in electric propulsion technology development and implementation. The work is designed to support JPL missions by successfully producing new EP and plume diagnostic technology, and infusing that technology into JPL projects. We plan to continue to focus on project and systems engineering needs, and maintain strong ties to university and other fundamental research activities to enhance the quality of this work.

There are many challenges to this effort. Since our effort is based on understanding the fundamental physics of the devices of interest and using that information to develop useful models of performance and life, a continued effort in modeling thrusters and spacecraft interactions, and performing laboratory research to provide data and benchmark the models, is required. Fortunately, the Advanced Propulsion Group at JPL is closely coupled to the JPL flight projects and often takes a leadership role in proposing and implementing electric propulsion systems in their missions. This close coupling provides valuable information flowing to the EP group on what technology and progress is needed for flight projects, and also detailed information from the EP group flowing back to the projects about what is possible in the project time frame. We thereby act as both an enabler and facilitator for electric propulsion implementation in NASA missions.

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